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TOP PHYSICS AT FUTURE COLLIDERS

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Abstract

This contribution summarizes a discussion of top quark physics beyond the LHC at the ECT* workshop "Old and new strong interactions from the LHC to future colliders" in Trento in September 2017. The text aims to present a brief review of the top quark physics potential of future lepton and hadron colliders. For five key measurements in top quark physics results of detailed studies into the prospects of hadron and lepton collider projects are reviewed. This summary identifies strengths and weaknesses of lepton and hadron colliders, and finds a clear complementarity between both types of machines.

1 Introduction

Forty-four years after the postulation of a third generation of quarks and twenty-two years after the experimental confirmation of the existence of the top quark, the field of top quark physics is dominated by a single installation. The LHC is producing millions of top quark each year. ATLAS and CMS, and even LHCb, produce a constant stream of results [1], surpassing the precision and sensitivity achieved at the Tevatron in many analyses.

At the same time several new colliders are being planned. A new high-energy hadron or lepton collider should come online by the time the LHC and its luminosity upgrade shut down. What top physics will be left for these machines to explore? And where can they make a real difference? In this contribution I will try to formulate a brief (and therefore necessarily somewhat sketchy) answer to these questions.

A more extensive write-up on top physics beyond the LHC, with some overlap with the current contribution, is found in Ref. [2].

2 Future colliders

In 2017 the field of particle physics is dominated by a single installation. And this will remain true for nearly two more decades. In the next years the LHC is envisaged to continue operation close to its design energy, gradually increasing the integrated luminosity available for analyses to approximately 300 fb^{-1}. After an upgrade of the accelerator complex, the high-luminosity phase (HL-LHC), will continue to collect data, increasing the sample to 3 ab^{-1} by the year 2037.

Possible large-scale particle-physics facilities beyond the LHC can be classified in two main types. A new high-energy hadron collider in the LEP/LHC tunnel can increase the center-of-mass energy achievable in proton-proton to 25-30 TeV (HE-LHC). A new ring with a circumference of up to 100 km is envisaged by the FCC project at CERN [3, 4, 5, 6] and in SPPC in China [7]. The main strengths of high-energy hadron colliders lie are the energy reach and production rate. An integrated luminosity of 10 ab^{-1} at 100 TeV yields approximately 10^{12} top quark pairs. Rare and unconfirmed associated production processes become accessible at such machines. Previously unexplored corner of phase space are unlocked, enhancing the sensitivity to massive new states.

The second category, that of e^+e^- colliders at the energy frontier, operates at lower center-of-mass energy. A circular e^+e^- collider with a circumference of 100 km can reach the top quark pair production threshold at $\sqrt{s} = 2m_t$. This possibility is under study in China (CEPC [7]) and in Europe (FCCee [8]). Linear colliders can explore higher energy, from 250 GeV to 1 TeV with the ILC [9]) or 350 GeV to 3 TeV with CLIC [10]). Both projects have developed a detailed staging scheme [11, 12, 13]. The strength of lepton colliders lies in precision measurements. Thanks to the benign environment, controlled initial state and the calculability of e^+e^- processes, a comparison of sub-% cross section measurement with Standard Model prediction of similar precision is possible at lepton colliders. Such measurements provide sensitivity to new physics at scales that are significantly beyond the direct reach of the machine. Moreover, as the top quark escaped scrutiny at previous lepton colliders, the main production process $e^+e^- \to t\bar{t}$ directly probes the $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices, that are not easily accessible at hadron colliders.

3 Top quark mass

Direct measurements of the top quark mass at the Tevatron and LHC reach an experimental precision of approximately 500 MeV, which may improve to 200-300 MeV with 3 ab^{-1} [14]. The interpretation and theory uncertainty of these measurements are subject of considerable debate [15, 16, 17], also at this workshop [18]. A better understanding of the interpretation and modelling uncertainties in parton shower and hadronization is required to take advantage of the improved experimental precision. The precision of extractions of the top quark pole mass from the (differential) top quark production cross section, which offer a more straightforward interpretation and theory uncertainty estimate, is expected to improve to the level of 1 GeVCMS-PAS-FTR-16-006,Alioli:2013mxa. To achieve sub-GeV precision theory development and improved experimental techniques are required. The ultimate potential of high-energy hadron colliders therefore remains hard to predict [6].

Lepton colliders offer the possiblity of scanning the center-of-mass energy through the top quark pair production threshold. An extraction of the top quark mass from the line shape [19] can offer excellent experimental [20, 21, 22] and theoretical precision [23, 24]. Provided a precise value of the strong coupling constant α_s is available, the total uncertainty can stay within 50 MeV [25].

4 Top quark interactions with SM gauge bosons

Hadron colliders primarily probe the strong interactions of the top quark. Future hig-energy hadron colliders can access a new kinematical regime of several TeV to several tens of TeV. Measurements of rates and asymmetries in highly boosted top quark production are sensitive to new massive mediators and yields stringent limits on the anomalous chromo-magnetic and chromo-electric dipole moments of the top quark [26] and the corresponding dimension-6 operators in an effective-field-theory extension of the SM [27, 28]. Exploitation of these data requires the development of new top-tagging techniques [29, 30].

The vertices of the top quark with electro-weak gauge bosons are probed at hadron colliders by measurements of top quark decay, single top quark production and associated $t\bar{t}V$ production [31] (with $V = \gamma, Z, W$). The HL-LHC and future higher-energy proton-proton colliders are expected to significantly improve the currently statistics-dominated measurements [32, 33, 34]. The ultimate potential depends on a strict control of theory and experimental systematic uncertainties [6].

Lepton colliders provide a complementary view: the $e^+e^- \to t\bar{t}$ process offers exquisite sensitivity to neutral EW gauge bosons [35, 36, 37, 38], while the strong interactions of the top quark can be tested with final-state gluon radiation [39]. The precision on the electric and weak dipole moments of the top quark that can be achieved in a relatively low-energy collider ($\sqrt{s}$ = 350-500 GeV) exceeds that of the HL-LHC by more than an order of magnitude and even exceeds the potential of the SPPC and FCChh projects. Adding data from operation at high energy ($\sqrt{s}$ = 1-3 TeV) helps to constrain four-fermion operators in a global fit [40].

5 Top-quark FCNC interactions

The discovery of flavour-changing neutral-current interactions of the top quark, highly suppressed in the SM, would be clear evidence of physics beyond the SM. Current limits on the branching ratios $t \to uX$ and $t \to cX$ are at the 10^{-3} level [41] are dominated by LHC searches for rare top decays. The HL-LHC is expected the $10^{-4} - 10^{-5}$ level [42]. FCChh and SPPC may access branching ratios as low as 10^{-7} [6], provided systematic limitation can be avoided.

Lepton colliders, with relatively small top quark smalles, clearly offer less potential for rare top quark decay searches, but may offer complementary information in a global analysis [43] and can offer competitive limits on FCNC interactions involving photons and Z-bosons. Searches for $e^+e^- \to tq$ production [44, 45] are possible at $\sqrt{s} < 350$ GeV. Operation above the $t\bar{t}$ threshold can provide limits on the $t \to cH$ and $t \to c\gamma$ branching ratios well below 10^{-4} [46, 47].

6 The top quark and the Higgs boson

Observation of associated $t\bar{t}H$ production provides a direct probe of the interactions between the two heaviest particles of the Standard Model. At the HL-LHC the direct measurement of the top quark Yukawa coupling is expected to reach a precision of 7-10% [48]. Therefore, a direct and precise determination of the top quark Yukawa coupling remains an excellent target for future colliders.

A 100 TeV pp collider can reach 1 % precision according to Ref. [49] by constructing cross-section ratios for very similar processes (i.e. $t\bar{t}H$ and $t\bar{t}Z$) and the use of techniques for boosted top quark production. At linear e^+e^- colliders the precision of the Yukawa coupling measurement reaches approximately 3-4 % [11, 50, 51] for center-of-mass energies in the range $\sqrt{s}$ = 0.55-1.5 TeV.

7 Summary and Outlook

The potential of future installations for five key areas of top quark physics is summarized in Table 1, taken from Ref. [2]. This summary lumps together a variety of studies, with different degrees of sophistication. Question marks indicate areas where no reliable estimates exist.

Table 1 demonstrates that the views on the top quark offered by lepton and hadron colliders are quite complementary: hadron colliders provide stringent limits on the strong interactions of the top quark at very high energy and FCNC interactions, while lepton colliders provide a precise characterization of the $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices and a superior top quark mass measurement. Both types of colliders offer excellent prospects to measure the top Yukawa coupling directly in $t\bar{t}H$ production, arguably the most interesting measurement among those discussed in this contribution.

Table 1: Summary table of top quark physics prospects from Ref. [2]. The current precision of several key measurement in top physics is compared to the projected evolution at the HL-LHC and two categories of future facilities. The HL-LHC prospects and the expected precision at future facilities are based on a highly non-uniform collection of studies, that include extrapolations, parton-level studies and full simulation studies. A more detailed description and references are given in the text.

project	today LEP/Tev/ LHC8	2037 HL-LHC	e^+e^- collider ILC/CLIC/ FCCee/CEPC	new pp collider FCChh/SPPC
$\sqrt{s}$	8 TeV	14 TeV	0.25-3 TeV	100 TeV
$\int \mathcal{L}$	20 fb^{-1}	3 ab^{-1}	0.5-4 ab^{-1}	20-30 ab^{-1}
m_t, exp. $\oplus$ theo. [MeV]	$500 \oplus 1000$	$200 \oplus ?$	$20 \oplus 50$	?
top QCD $\lvert d_V\rvert$,$\lvert d_A\rvert$	< 0.02, < 0.09	< 0.01, < 0.02	?	< 0.003
top Yukawa (direct)	O (100%)	7-10 %	~ 4 %	1 %
FCNC $BR(t \to qX)$	$\sim 10^{-3}$	$10^{-5} - 10^{-4}$	$\sim 10^{-4}$	$\sim 10^{-7}$?
$t\bar{t}Z$ form factors	-	0.03-0.3	0.002-0.005	0.01-0.07

A precise characterization of top quark production in high-energy electron-positron or proton-proton collisions provides a stringent consistency check of the Standard Model and offers excellent sensitivity to high-scale new physics.

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